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Advanced approach for a demand-oriented fluid supply in grinding

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ABSTRACT

The productivity of grinding processes is often limited by the risk of thermal damage of the workpiece surface layer. Therefore, the control of thermal conditions in the grinding arc is of utmost importance for both, industrial practice and academia. In order to optimize the application of the metal working fluid in grinding, devices and methodologies are needed which can assure the measurement of temperatures in grinding or within set-up mode and the control of demand-oriented fluid supply parameters (nozzle angle, nozzle height, nozzle outlet area, fluid jet velocity). The systematic use of such devices and methodologies for fluid supply optimization is enabling reliable and economic grinding processes.

1. Introduction and state-of-the-art

In grinding, most of the heat generated due to high friction between the abrasive grains and the workpiece material is dissipated through the surface layer of the workpiece [1] and causes major challenges for the generation [2] and assessment of favourable surface integrity [3]. If the thermal load of the workpiece exceeds certain limits, thermal damage of the workpiece material (grinding burn) occurs which is accompanied by a decrease in hardness, a change in microstructure or a change in the residual stress state [4]. Thus, the efficient supply of metal working fluids (MWF) in grinding plays a key role in controlling the thermal conditions in the grinding arc. However, the suitable MWF supply in grinding is dependent on various parameters which are the MWF flowrate, the jet velocity, the jet shape, the nozzle position [5], and the wheel specifications (especially the wheel porosity) [6]. Regarding the required MWF flowrate, different suggestions have been presented in literature: a comparably simple flowrate model based on the spindle power P_s during the grinding process has been suggested by Silliman [7] who proposes a specific MWF flowrate of 8–10 l/(min·kW), but neglects aspects like wheel speed, MWF type as well as type of abrasive or mode of grinding process. Based on the investigations of Ott [8], Metzger [9] presented a model for the prediction of a minimum MWF flowrate Q_{MWF} in grinding which considers in addition to the spindle power P_s the nozzle efficiency η, the specific heat capacity C of the used MWF and its density ρ as well as its tolerated temperature rise $\Delta\theta$. Webster et al. [4] reviewed the mentioned MWF flowrate models and compared them with results obtained by using an experimental procedure for the evaluation of MWF supply conditions in grinding. It can be concluded that in addition to the MWF flowrate, the wheel speed has an influence on the avoidance of grinding burn. Independent from the wheel speed, a specific flowrate of at least 4 l/(min·mm) was sufficient to achieve the desired surface integrity of the ground parts. In general, the models and methods developed within the recent studies are useful for rough estimations to ensure the prevention of grinding burn.

Also many research activities in the past have been focussed on the nozzle design. Besides the traditional tangential or free flow nozzle, different nozzle designs (e.g. the nozzle profile by Rouse et al. [10]) have been developed to maintain the jet's initial shape over long distances [11]. Also, the jet-speed/wheel-speed-ratio has been addressed which should match a value between 0.8 and 1.0 to achieve a sufficient MWF supply [5].

A further aspect influencing the MWF supply conditions in grinding is the adequate positioning of the nozzle. Engineer et al. achieved best results with a nozzle position as close as possible to the contact area [12]. Vits [13] and Ott [8] recommended that the MWF jet should hit the grinding wheel tangentially at approximately 10°–25° in front of the contact zone. However, this large range for the recommended nozzle angle carries the risk of substantial variations of the thermal impact affecting the workpiece material.

To summarize this review of influencing factors regarding MWF supply in grinding, a lot of generalized recommendations for MWF flowrate, jet velocity, nozzle design and nozzle position can be derived from literature. However, the different methods and models do neither consider real temperatures in the contact area nor can they ensure the lowest thermal load in grinding. Thus, to determine optimal MWF supply conditions for a given grinding process, devices and methodologies to control the MWF supply parameters are needed. Ideally, these devices adapt the supply parameters to the needs of the specific grinding process by using in-process information like forces, power or grinding temperature. This paper presents an approach which eases practical application making use of a stepwise procedure explained in Section 2. By optimizing the MWF supply in grinding, economic and environmental aspects are addressed simultaneously as optimized MWF supply conditions allow for an increased productivity and energy efficiency as well as a reduction of the amount of MWF needed.

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2. Approach towards an optimized MWF supply in grinding

Aim of the research approach presented within this paper is the development of an automated device to identify and to control the best possible and demand-oriented MWF supply conditions in grinding by means of an optimizing algorithm (cf. Fig. 1). For this purpose, a stepwise procedure has been set up: in a first step, the optimal nozzle design has been selected with regard to jet coherency and jet speed by using high-speed imaging techniques (cf. Section 2.1). These techniques allow for the assessment of the jet coherency in a qualitative and of the jet speed in a quantitative way.

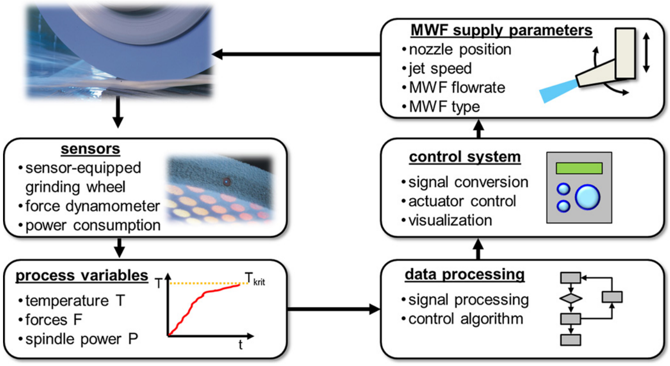

Fig. 1. Control loop for demand-oriented MWF supply in grinding.

After the evaluation of the nozzle design, the optimal coupling between the MWF jet and the rotating wheel has been studied with a test rig in set-up mode (cf. Section 2.2). This test rig can be used to determine the optimal nozzle position regarding distance to the grinding arc, nozzle height, nozzle angle, and MWF jet speed/MWF flowrate. For the reliable positioning of the MWF supply nozzle and setting of MWF jet speed/MWF flowrate an automated motor-driven system has been realized (cf. Fig. 2).

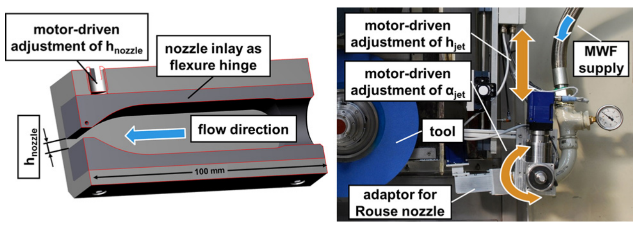

Fig. 2. Left: flat jet nozzle with an inner profile based on Rouse (designed as flexure hinge). Right: automated motor-driven MWF supply system.

Finally, an infrared-(IR)-sensor equipped tool (Thermo-Grind-system) has been used to prove if the MWF supply conditions obtained within the two steps described above allow for the lowest possible thermal impact in grinding (cf. Section 2.3). The Thermo-Grind-system enables monitoring of the thermal impact on each workpiece and verification of the optimal MWF supply parameters.

2.1. Design of MWF supply nozzle

As mentioned above, the selection of an appropriate nozzle design in grinding has a major impact on the MWF supply conditions to the grinding arc due to the associated jet quality. To characterize the jet quality and according to this, the effectiveness of different nozzle designs, high-speed imaging techniques can be used. For this purpose, two different nozzle designs have been investigated: a traditional (tangential) nozzle was compared with a flat nozzle design based on Rouse. The Rouse nozzle with a width of 30 mm has been designed as a flexure hinge so that the nozzle outlet height h_{nozzle} can be varied in a range of 0.5–1.5 mm (cf. Fig. 2). Thus, varying MWF jet flowrates respecting constant MWF jet velocities can be set and ensured. As a result, the nozzle with an inner profile based on Rouse is characterized by a higher jet coherency over a long distance after the nozzle orifice without any visible jet dispersion or widening independent from MWF flowrate and jet speed. Thus, this nozzle design has been used for the investigations described within this paper.

2.2. Test rig for analysing the MWF supply in the set-up mode

Based on the investigations of Powell [14], a test rig which enables a temperature measurement beneath the contact area between the grinding wheel and the workpiece under very similar conditions compared to a real grinding process was developed [15]. The grinding wheel is plunged and thus replicated into a workpiece which is mounted on a heating plate. After reaching the specified area which is heated up electrically, the translational motion between the grinding wheel and the test rig is stopped (v_{ft} = 0 m/min), whereas the rotation of the grinding wheel is continued (cf. Fig. 3). Furthermore, a thermocouple is placed slightly beneath the grinding arc in the middle of the heated area to log the temperature change during the trials. A change of the MWF supply conditions will result in a change of the measured temperature at constant electrical heating power. Thus, the differing MWF supply parameters which are to be set during the investigations can be directly correlated with the temperature evolution below the grinding arc.

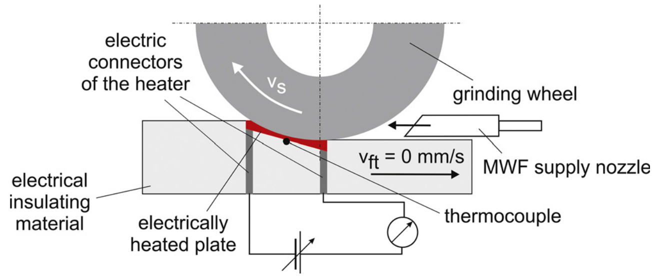

Fig. 3. Test rig to analyse MWF supply conditions (schematic).

Although the described system is limited to the use in the set-up state of grinding processes at comparably low temperatures, it represents a quick and effective approach to generate knowledge how MWF supply conditions can be improved. Hence, influences of the MWF supply parameters, of the MWF type as well as of the nozzle design can be observed without performing real grinding operations.

2.3. In-process temperature measurement

A key approach to obtain in-process information about the influence of the MWF supply conditions on the temperature in the contact area is the usage of sensor-equipped grinding wheels. From the first studies which have shown the ability of a tool-integrated temperature measurement to gain in-process information directly from the contact zone, the measurement technique has been constantly improved. Today, a fast IR-photodiode detects the IR-radiation from the contact zone via an optical fibre (cf. Fig. 4), both embedded in the grinding wheel [16].

The data received from the IR-sensor are filtered, transformed into temperatures (after calibration) and condensed by a data box directly on the wheel. The data are transmitted wireless to an evaluation box or a PC for monitoring purposes. In view of the

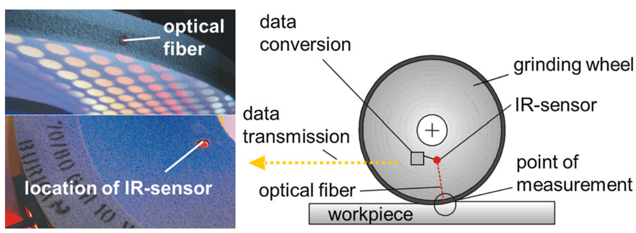

Fig. 4. Sensor-equipped grinding wheel for temperature measurement (Thermo-Grind-system).

investigations presented within this paper, the Thermo-Grind-system has been used to identify optimal MWF supply parameters evaluated with the above described test rig.

2.4. Systematic optimization of nozzle positioning and MWF supply

In practice, nozzle positions are often more or less undefined and not adjustable in a reproducible way as indicating positions are missing. To overcome these limitations, a motorized system has been realized which allows for an automated motor-driven adjustment of nozzle height h_{jet}, nozzle angle α_{jet}, and nozzle orifice height h_{nozzle} based on measured temperatures in grinding and by means of an optimizing algorithm. For the setup and verification of the developed system, temperature information received from the two methods described within Sections 2.2 and 2.3 have been used to find optimized MWF supply conditions. An evolutionary algorithm and the bisection method have been considered and assessed with regard to time needed as well as reliability to find local and global temperature minima dependent on the adjustment of nozzle height h_{jet}, nozzle angle α_{jet}, jet velocity v_{jet}, and MWF flowrate Q_{MWF} (varied by nozzle orifice area at constant jet velocity). It has been found that the bisection method needs significantly less iteration steps (in a range of three to seven steps) and time to identify e.g. the optimal nozzle height position h_{jet} which assures minimal temperatures in the grinding arc (cf. Fig. 5).

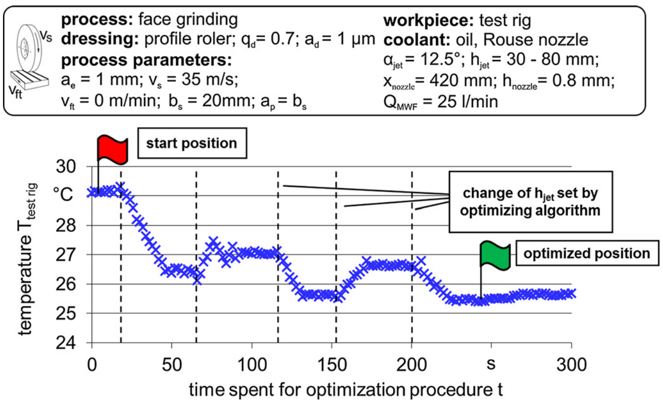

Fig. 5. Influence of nozzle height on temperature beneath the contact zone (measured by test rig, determined by optimizing algorithm).

As Fig. 5 shows, the selected algorithm allows for the optimization of the nozzle height position even at comparably low absolute temperatures beneath the contact zone. Minor changes of the temperature caused by the automated nozzle height variation are well detectable. Furthermore it can be derived from the results that after about 4 min an optimized height position for the MWF supply nozzle has been found.

3. Experimental results

3.1. Determination of temperature-maps

In order to set up the system for an automated control of differing MWF supply conditions, the test-rig according to Powell (see above) has been used. In this regard, the dependency between the temperatures beneath the contact zone in grinding, the nozzle height h_{jet} and the nozzle angle α_{jet} have been checked to prove if local minima exist (cf. Fig. 6; parameters identical to the details given in Fig. 5). The existence of these minima is a prerequisite to apply the bisection-method-algorithm for the optimization of the MWF supply parameters. The results gained show the importance of an optimized positioning of MWF supply nozzles. MWF supply conditions (flowrate, jet speed) are further essential influencing factors. By using the Thermo-Grind-system these factors were evaluated as well (cf. Section 3.2).

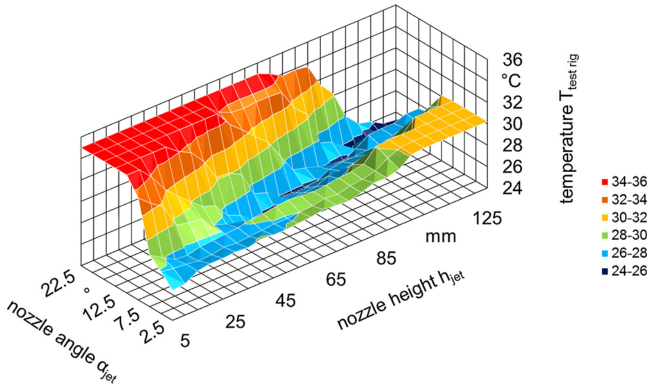

Fig. 6. Influence of nozzle position (height and angle) on temperature beneath the contact zone (measured by test rig).

In addition, it can be taken from Fig. 6 that the parameters for nozzle position mutually influence each other as each optimum nozzle height requires a different optimized nozzle angle.

3.2. In-process temperature measurement and MWF supply optimization

In order to verify the findings gained with the test rig according to Powell, single-stage grinding processes with constant parameters (details given in Fig. 7) have been performed using the Thermo-Grind-system to log the temperatures in the grinding arc. The varied MWF supply parameters are indicated within the figures. In a first step, the investigations aimed at the definition of the optimum jet-speed/wheel-speed-ratio (cf. Fig. 7): For a constant wheel speed v_s = 35 m/s and a constant MWF flowrate Q_{MWF} = 32 l/min, the MWF jet speed v_{jet} was varied in the range of 21.0–45.5 m/s. The different MWF jet speeds at constant MWF flowrate were realized by the motorized adjustment of the nozzle orifice height in a range of 0.5–1.5 mm (cf. Section 2.1). The nozzle position has been set at a nozzle angle of α_{jet} = 12.5° at a nozzle height of h_{jet} = 88.3 mm. These settings led to a minimal temperature in the contact zone when applying the test rig.

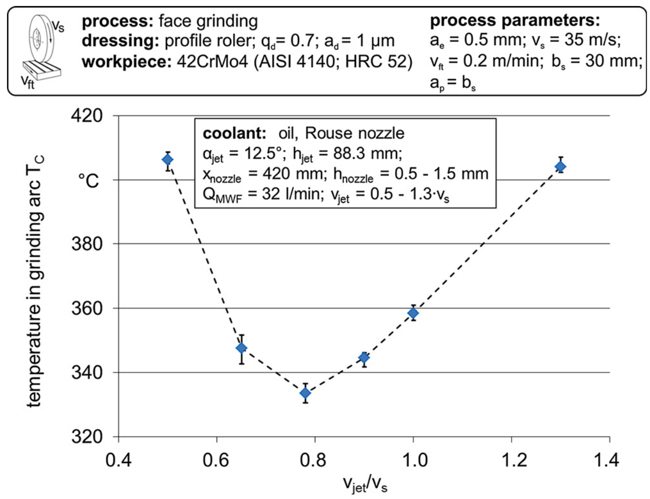

Fig. 7. Temperature in the grinding arc dependent on jet-speed/wheel-speed-ratio (determined by using the Thermo-Grind-system).

Fig. 7 shows for the chosen grinding conditions that a minimal temperature in the contact zone can be obtained by setting a jet-speed/wheel-speed-ratio of 0.78. This value is slightly below the lowest recommended value for the jet-speed/wheel-speed-ratio given in literature. Furthermore, the results in Fig. 7 indicate that a variation of the speed-ratio in the range between 0.8 and 1.0 causes a distinct change of the temperature in the grinding arc. This shows that beside the nozzle position the MWF jet speed represents another crucial aspect with regard to optimized MWF supply conditions.

An optimal height position of the MWF nozzle for the given process configuration lies in the range of approx. $h_{jet} = 90$ mm ($\alpha_{jet} = 12.5^\circ$) (cf. Fig. 8). Under these conditions, the jet hits the wheel tangentially which is in full agreement with observations reported in literature. For a complete set of optimized MWF supply parameters a third step which identifies suitable MWF flowrates is necessary (cf. Fig. 9).

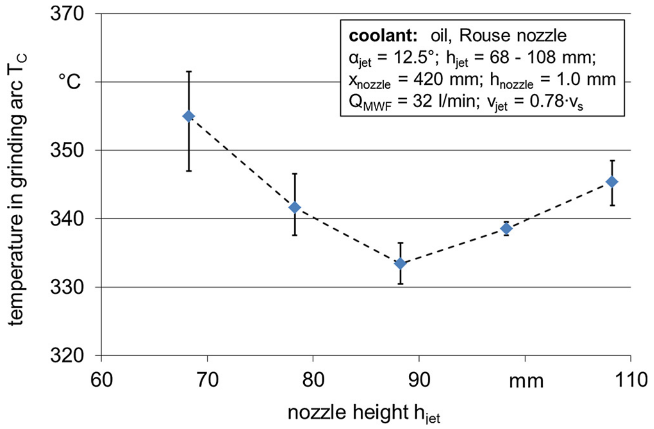

Fig. 8. Temperature in the grinding arc dependent on nozzle height (determined by using the Thermo-Grind-system).

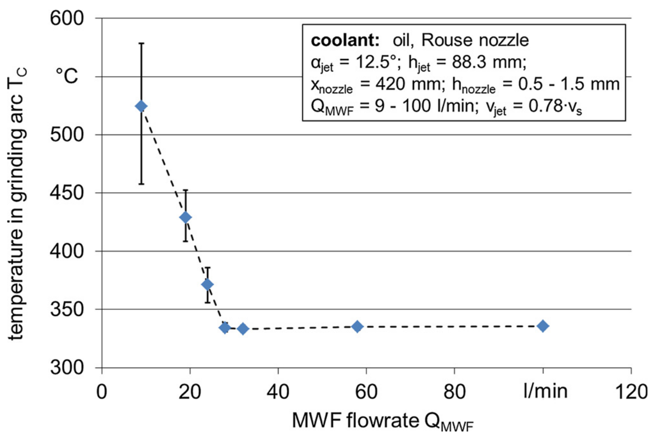

Fig. 9. Temperature in the grinding arc dependent on MWF flowrate (determined by using the Thermo-Grind-system).

The results in Fig. 9 show that for the given configuration, a flowrate of $Q_{MWF} = 32$ l/min ensures minimal temperatures. An increase of the MWF flowrate above 32 l/min causes no further reduction of the temperature in the grinding arc. This result indicates a clear potential to enhance the energy efficiency in grinding by identifying process specific minimum MWF flowrates. Thus, avoidance of high energy consumption and of an over-supply with MWF in grinding can be realized. Also, reduced and demand-oriented MWF flowrates would require a much lower tank capacity of the MWF supply system and would at least lead to lower amounts of MWF-disposal.

4. Conclusions and outlook

The presented results show that the MWF supply in grinding is a crucial aspect with significant optimizing potential. By using systems as the described test rig in combination with an automated motor-driven nozzle positioning, optimal and demand-oriented MWF supply parameters can be determined. A closed-loop control which allows for an adjustment of the MWF supply to achieve the lowest possible thermal impact on the workpiece in grinding enables a simplified determination of optimal MWF supply parameters. The system furthermore carries the potential to increase energy efficiency by a targeted choice of supply parameters, which do not lead to the lowest temperatures but to temperatures which are sufficient to reliably avoid thermal damage. However, this approach would require knowledge regarding process specific temperature thresholds. Also, temperature maps showing the dependency between the different MWF supply parameters and the temperature rise in the grinding arc can be gained. The Thermo-Grind-system in combination with an automated motorized system for the adjustment of MWF supply parameters can be used to prove and also to identify optimal settings in a fast and effective way.

Future research activities will focus on the full integration of the Thermo-Grind-system and the MWF supply control system into the environment of a grinding machine in order to allow for monitoring and closed-loop control of the MWF supply conditions during grinding. The use of the Thermo-Grind-system for temperature monitoring and control of grinding processes will enable the continuous monitoring of the thermal impact on the workpiece surface layer with regard to surface integrity. Changes of surface layer properties are a function of the temperature and of the exposure time of the surface temperature at the workpiece which is given e.g. by the feed speed. In this context, the development of so-called time-temperature-diagrams will provide information about the resulting surface and subsurface properties caused by a thermal impact in a specific grinding process and allows for the determination of the required process specific temperature thresholds [17].

Acknowledgments

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